

# Quantum Measurements and Standards Based on Condensed Matter Physics

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# Fundamental Standards and Nanotechnology

## Context of this talk:

- Renewed focus at NIST on its traditional measurement and science mission [requiring world leadership in fundamental standards]
- Practical use of nanotechnology (SFA) toward that end

From the June, 2003, VCAT minutes:

The Senior Management Board (SMB) Retreat identified five goals for 2003 and 2004, and in this talk he discussed the first goal - "Reaffirm NIST's role as the leader of the Nation's measurement system and define how best to carry out that role and maximize impact in a changing global environment." The SMB perceived the need for NIST to reaffirm its commitment to its traditional measurement and science mission, to enhance its national leadership, and to maximize the impact of its work. The need to focus on its traditional measurement and science mission was highlighted in responses from the recent employee survey.

# Intrinsic Measurements

- Make measurements based on counting small quantities
- Base on a naturally occurring quantum

For example:

Time                      9 192 631 770 periods of a transition in a cesium-133 atom.

Length                    HeNe laser operating at 633 nm

Voltage                    $\phi_0 = h/2e$                    magnetic flux quantum in superconductors

Current/capacitance     $e$                    charge on an electron

Resistance                $h/e^2$                    quantum Hall resistance

Photons                    $h\nu$                    the energy of a radiation quantum

# The Beginnings

A commercially failed superconducting Josephson computer technology in the early 1980s left a fabrication legacy that has made possible exceptional success at NIST:

- 34 years of nanotechnology
- Profound impact on standards and measurements

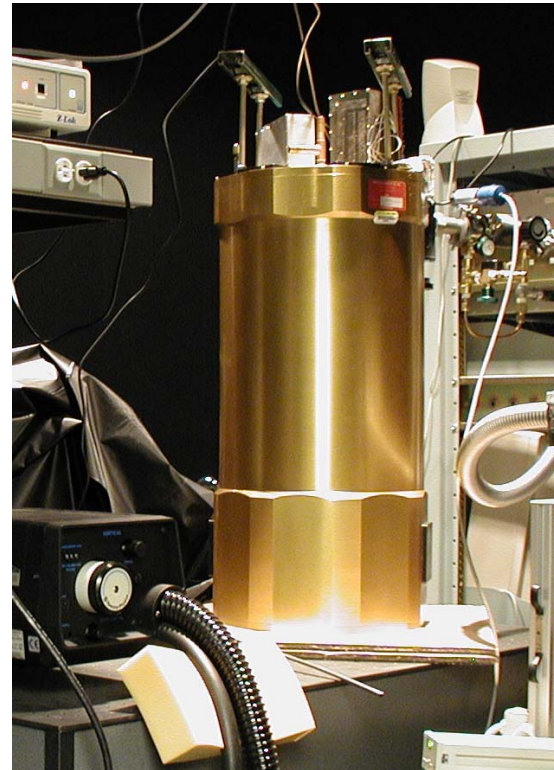
# Practical Keys to Success

## Integrated circuit fabrication



Well equipped Class  
100 clean room

## Easy cooling



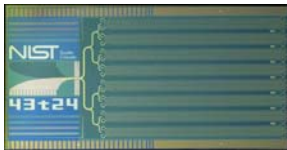
Adiabatic demag-  
netization refrigerator  
50 mK

# Electromagnetic Technology Division NIST Collaborations

Organization	Topic	Funding
Physics	Ion traps for atomic clocks and quantum computing	Competence
	Submillimeter tomographic spectroscopy	ATP
	Single electron counting	
Physics and ITL	Optical photon counting for quantum key distribution	ATP
	Quantum computing	Competence
CSTL	Johnson noise thermometry	Competence
	Ultra-high resolution x-ray detection for materials analysis	
EEEL (Optoelectronics)	Single photon generation	Competence
EEEL (Electricity)	Programmable voltage standard	
	Quantum-based arbitrary waveform generator (ac voltage standard)	
	Single electron tunneling capacitance standard	Formerly Competence
	Metrology triangle	

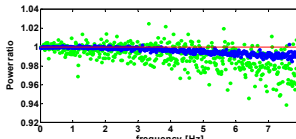
# Today's Examples: Standards and Measurements

All based on condensed matter quantum phenomena



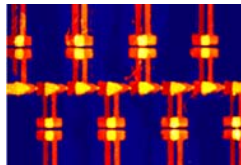
Voltage standards ★

Magnetic flux quantum



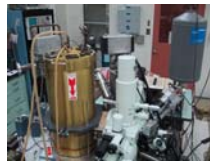
Temperature standards ★

Magnetic flux quantum



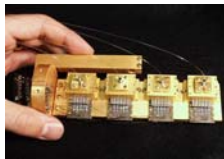
Capacitance standards ★

Electron charge



Infrared and x-ray imaging ★

Photon



Optical photon counting ★

Photon

★ Best-in-the-world

# Josephson Voltage Standards

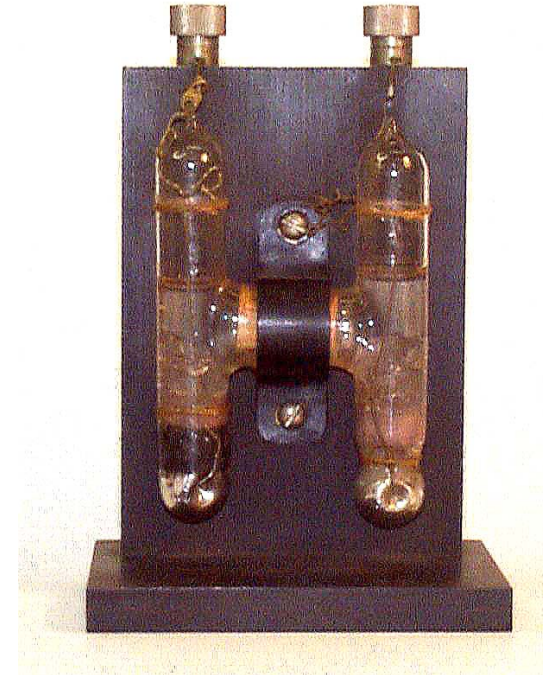
Three generations of series array Josephson voltage standards:

- dc
- Programmable
- Arbitrary waveform synthesizers

# Artifacts vs. Quantum-based Standards

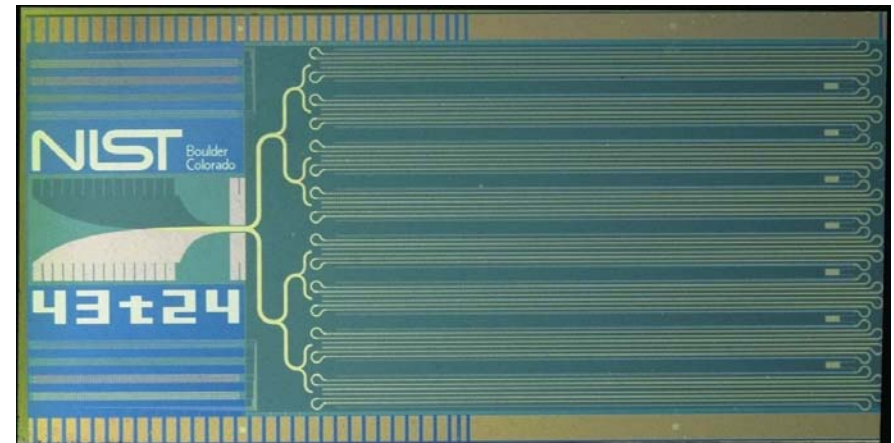
- **Electrochemical Cells**

- 1794 First Cell
  - Volta
- 1908 Cd-Hg      1.0186 V
  - Weston



- **Superconducting Josephson junctions**

- Single junctions 1962 - 68
- Arrays 1983 - present



# The Shapiro Effect

- How it works

- Sinusoidal drive frequency,  $f$
- Constant-voltage steps

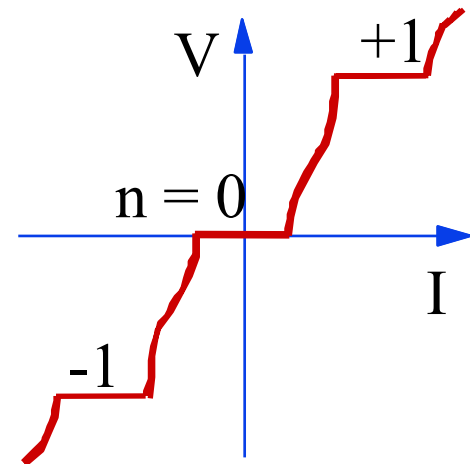
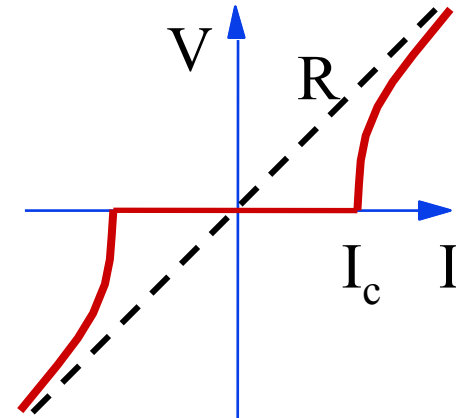
$$V_n = \frac{h}{2e} n f$$

$$h/2e \approx 2 \mu\text{V}/\text{GHz}$$

- Josephson constant

$$2e/h \approx K_J \equiv 483\,597.9 \text{ GHz/V}$$

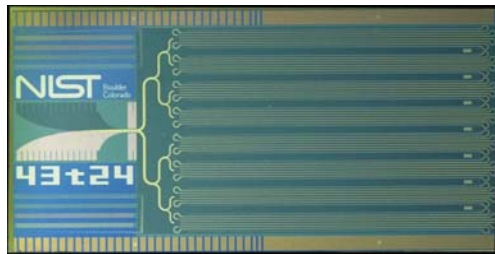
- Equivalent to counting flux quanta



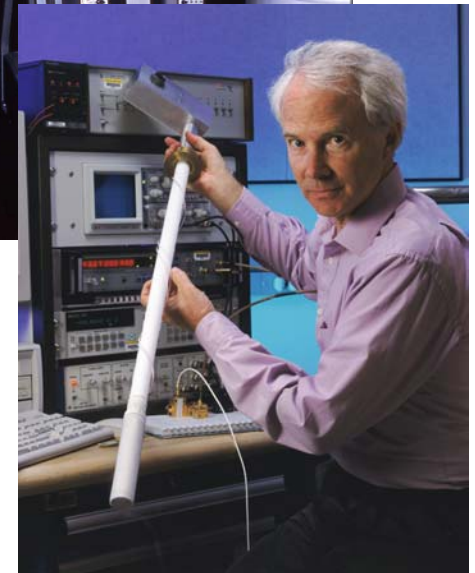
# Conventional DC Series Array Josephson Voltage Standard

## First Generation

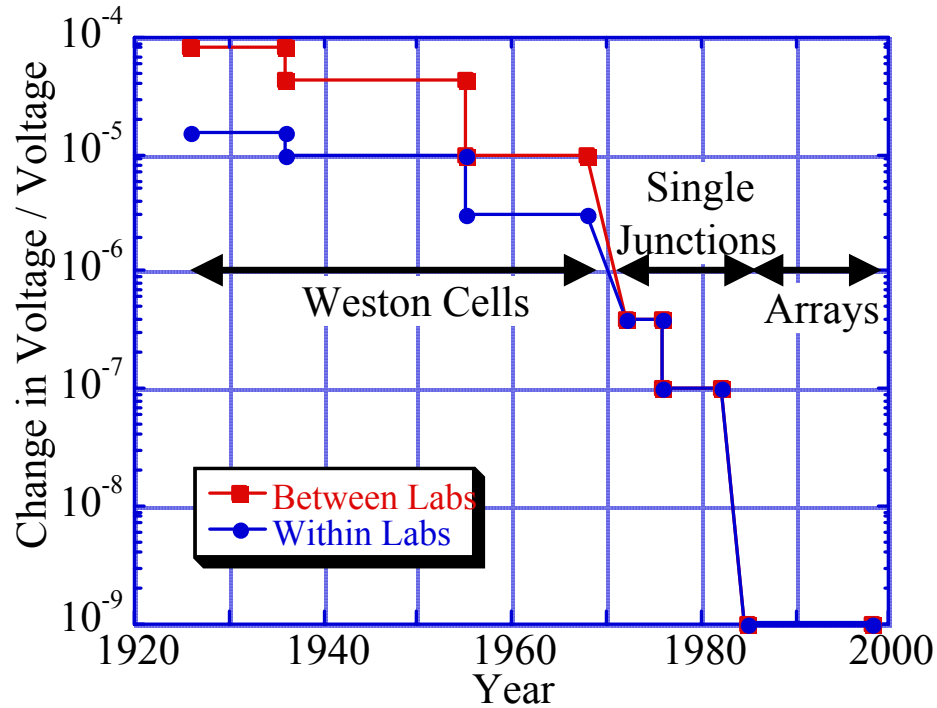
- Arrays of 20,000 junctions required to increase voltage to 10 volts



- Reproducible with junctions of any materials to 2 parts in  $10^{19}$
- Systems operating in more than 70 laboratories
- Available commercially from two sources



# DC Voltage Standard Comparison



From Bachmair, 1988 and Hamilton, 1998

	Artifact	Quantum
Cell/Array Uncertainty:	Parts in $10^6$	Parts in $10^9$
Reproducibility:	Parts in $10^5$	Parts in $10^9$

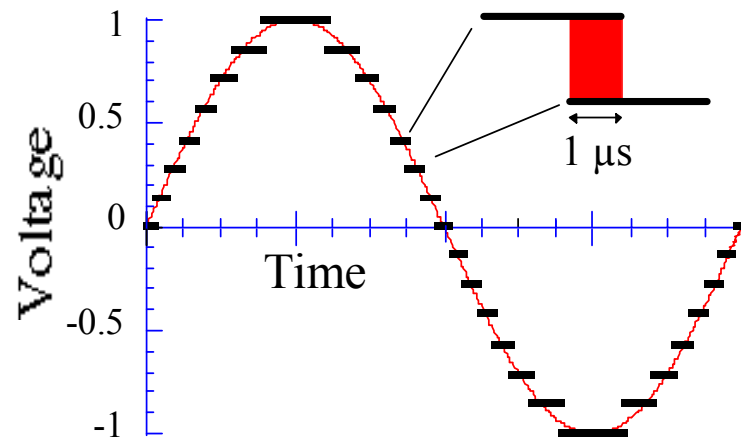
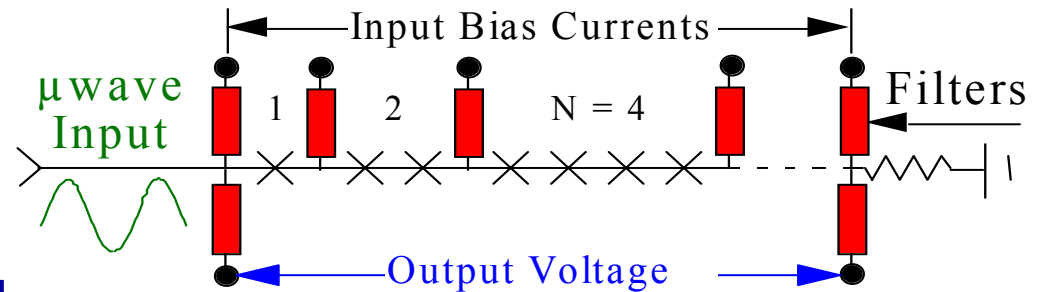
# Problems with dc Voltage Standards

- Changing voltage very difficult
- Electrical noise can cause junction to jump steps
- Would like a quantum-based ac voltage standard

# Programmable Voltage Standard

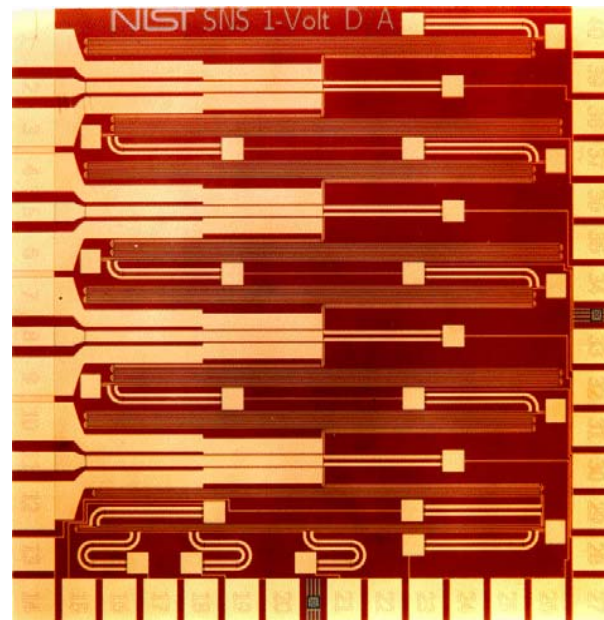
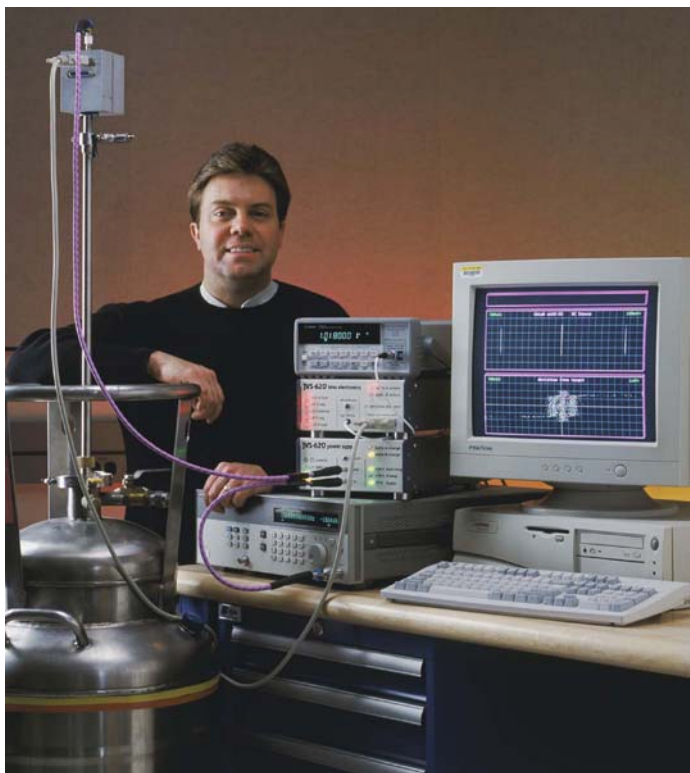
## Second Generation

- Binary sequence array
  - 32,768 Josephson junctions
- Accuracy is limited by speed of the semiconductor current drivers ( $\approx 1 \mu\text{s}$ )
- AC waveforms with accurate  $V(t)$  only at milliHz



# Programmable DC Standard System

- 1 V chip
- 32,768 junctions
- About 10 systems worldwide



- Intrinsically stable voltage steps
- Programmable from +1.1 to -1.1 V
- 1  $\mu$ s settling time
- Complete, fully automated system
- High noise immunity allows direct connections

# Arbitrary Waveform Synthesizers

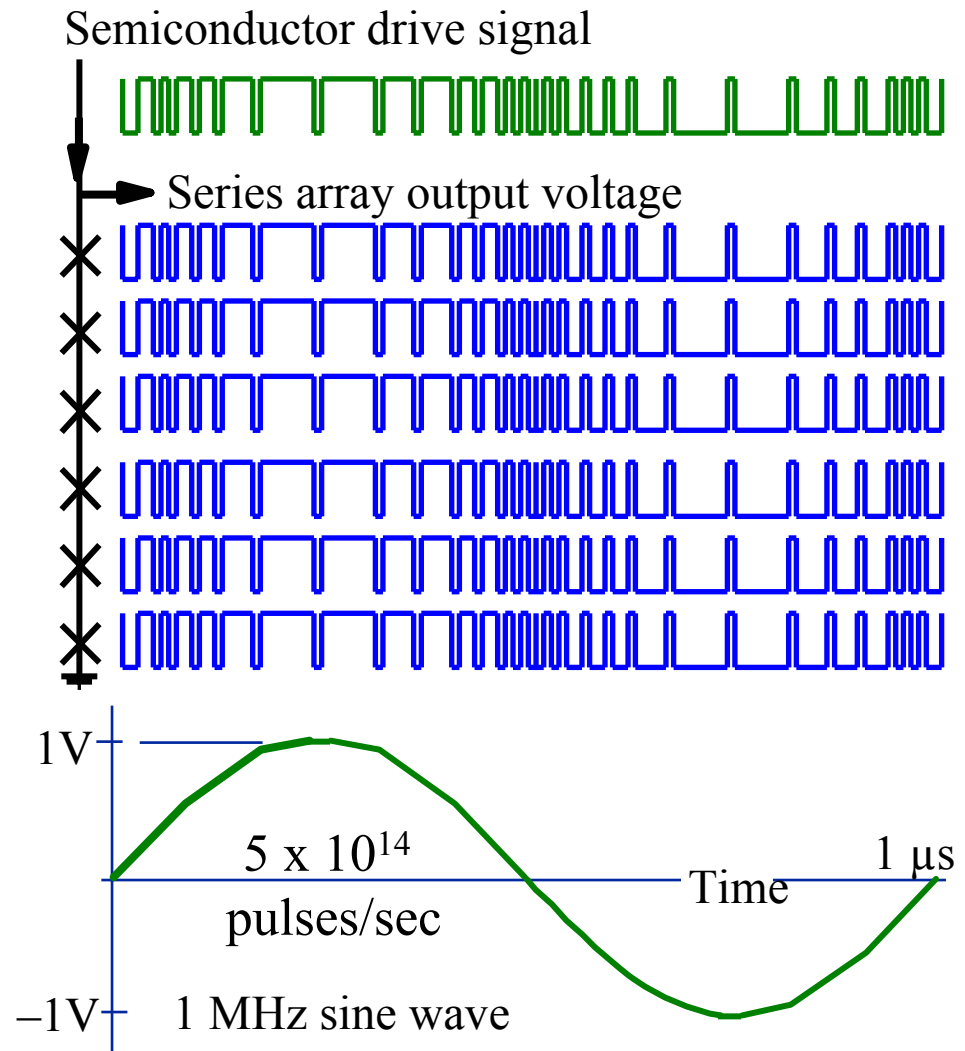
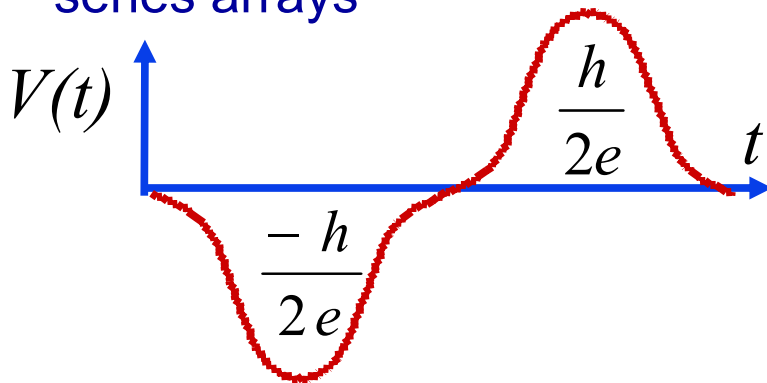
## Third Generation

- Features
  - Quantum-based ac voltage source
  - Stable ac voltages
  - Programmable arbitrary waveforms
  - Combine dc, ac and arbitrary wave-form functions in a single standard

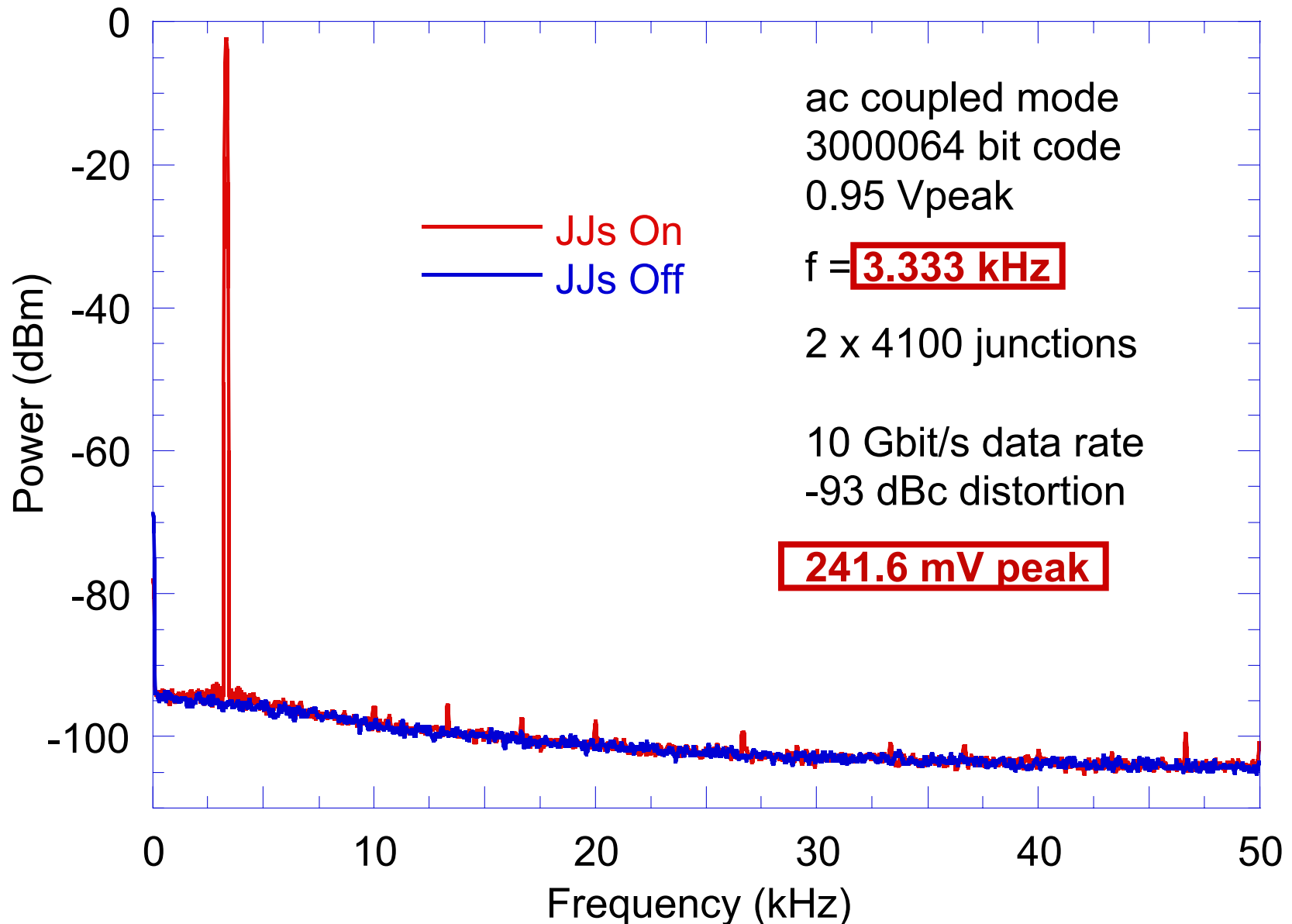


# Digital-to-Analog Waveform Synthesis

- Drive with pulses rather than sine wave — string of 1s and 0s
- Quantized pulses recreate desired ideal waveform
- Increase output voltage with series arrays



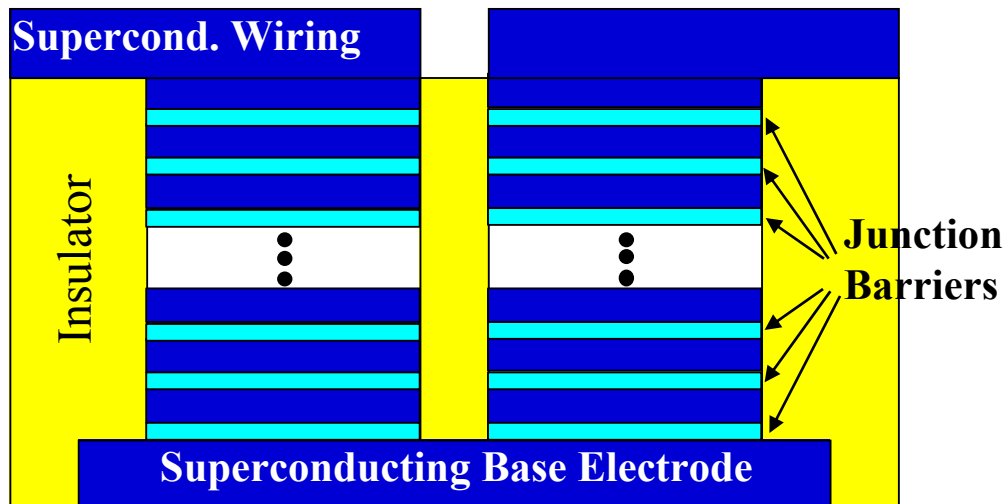
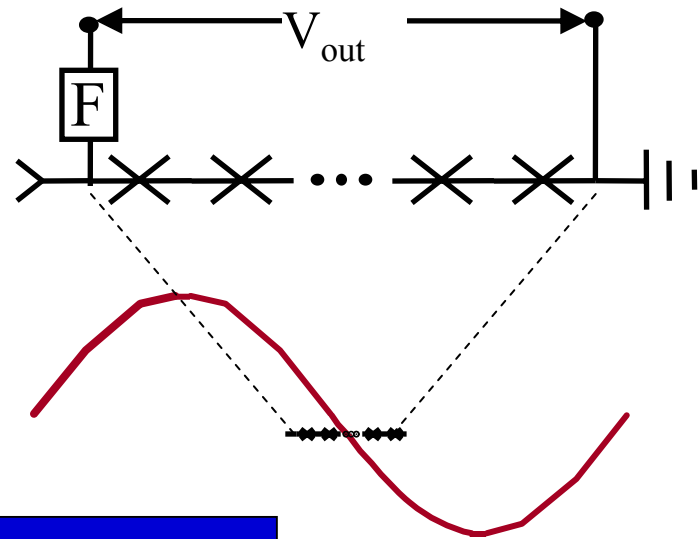
# August 2002 Record Output Voltage



# Lumped Arrays

- Increase output voltage and improve performance of Josephson voltage standard systems
- 50-100 nm junction spacing is required!
- Must develop nanoscale fabrication technology

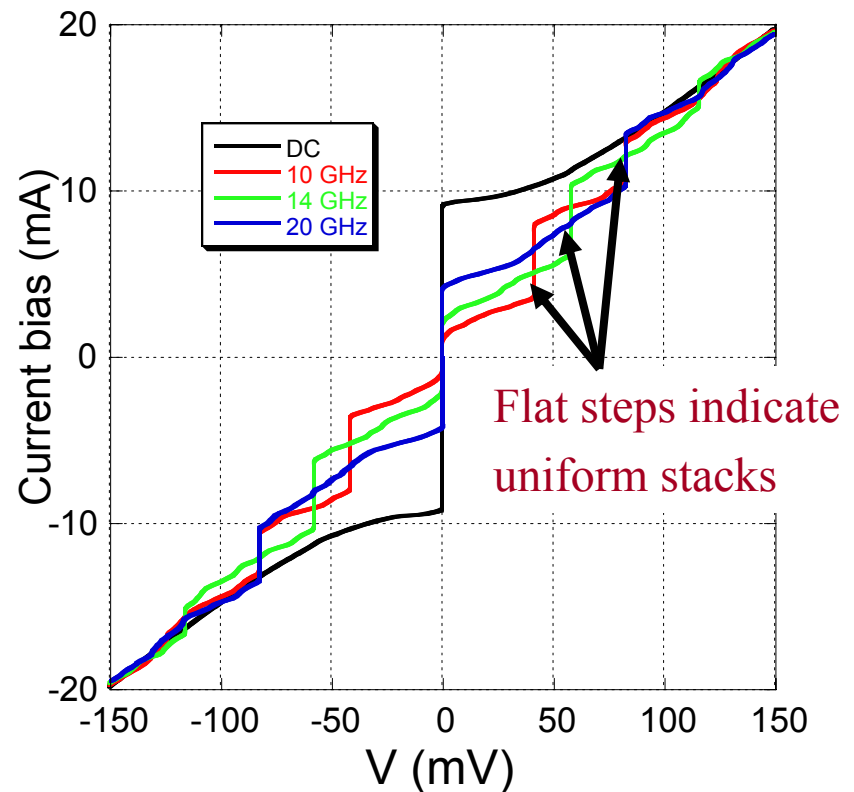
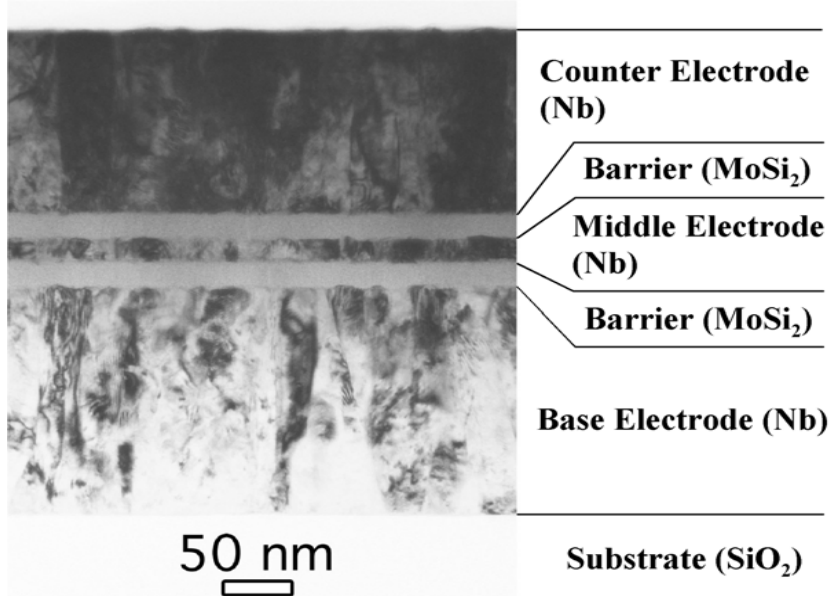
Total array length  $\ll \lambda/4$  wavelength



# Nanoscale Stacked Junction Arrays

Nanoscale high-density Josephson arrays will increase the performance of quantum-based voltage standards.

Demonstrated 27 nm junction spacing with 5 nm electrodes!



- Cross-sectional TEM image of a five layer Nb-MoSi<sub>2</sub>-Nb-MoSi<sub>2</sub>-Nb film.
- Each MoSi<sub>2</sub> barrier is 23 nm thick.
- Middle electrode thickness is 20 nm.

# Johnson Noise Thermometry

- A purely electrical temperature standard to complement efforts in gas-based standards
- Potential to be a primary standard
- Electronic “kelvin”
- Boltzmann’s constant

What we hope to replace ...



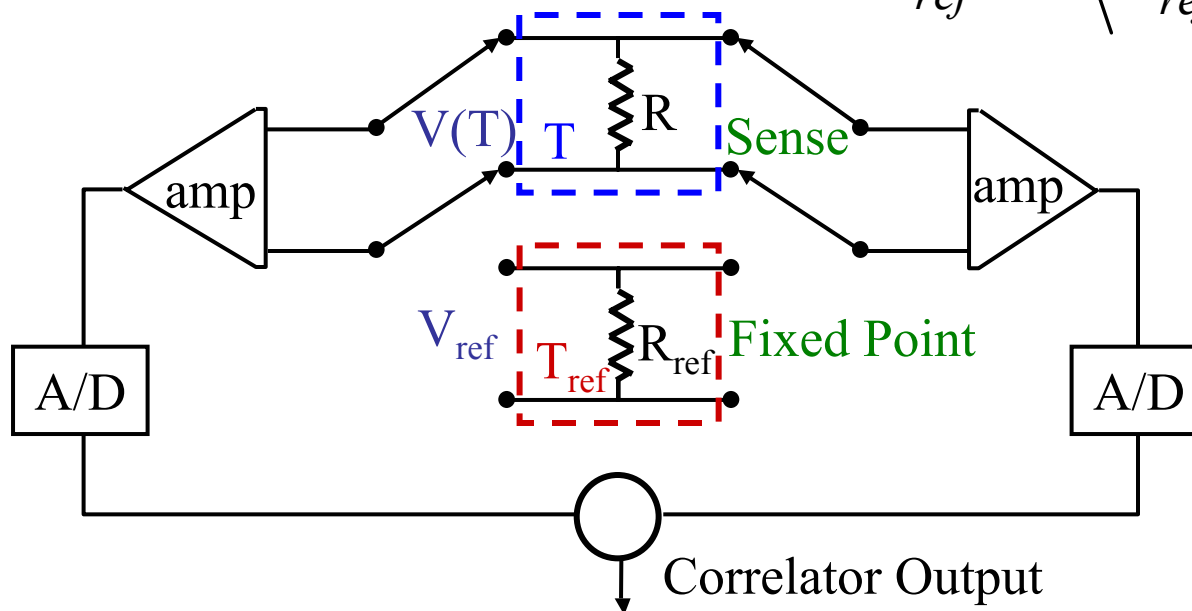
Joint program with CSTL

# Johnson Noise Thermometry (JNT)

- Voltage noise of a resistor
  - Nyquist 1928
- Fixed-point temperature comparisons

$$\langle V_T^2 \rangle = 4kTR\Delta f$$

$$\frac{T}{T_{ref}} = \frac{\langle V^2(T) \rangle / R}{\langle V_{ref}^2 \rangle / R_{ref}}$$

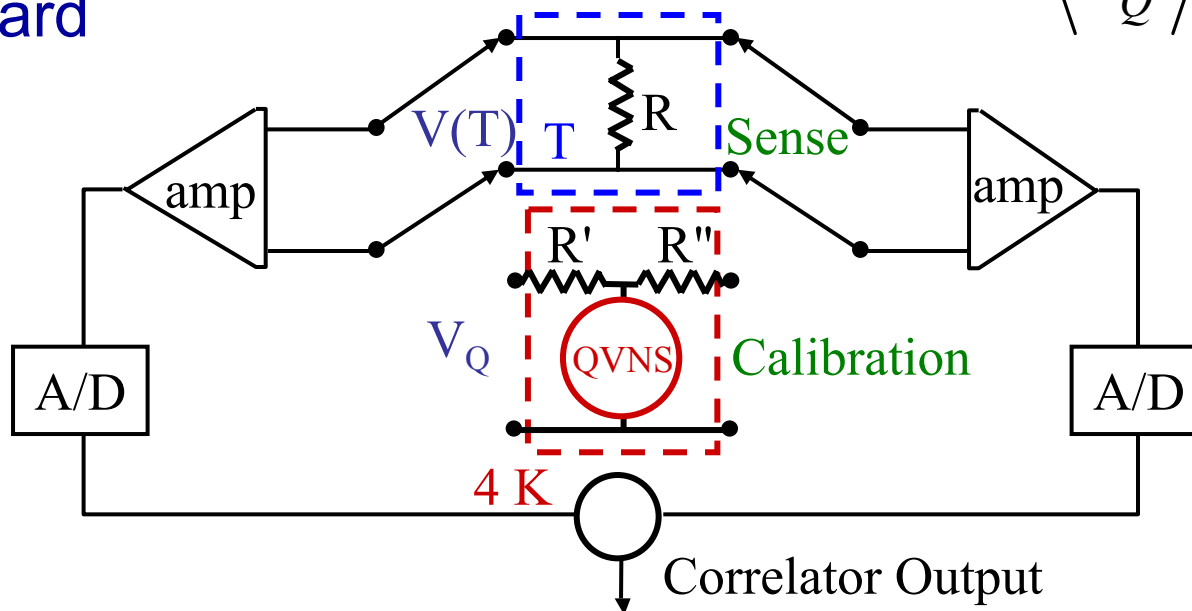


# Quantized Voltage Noise Source Calibrator

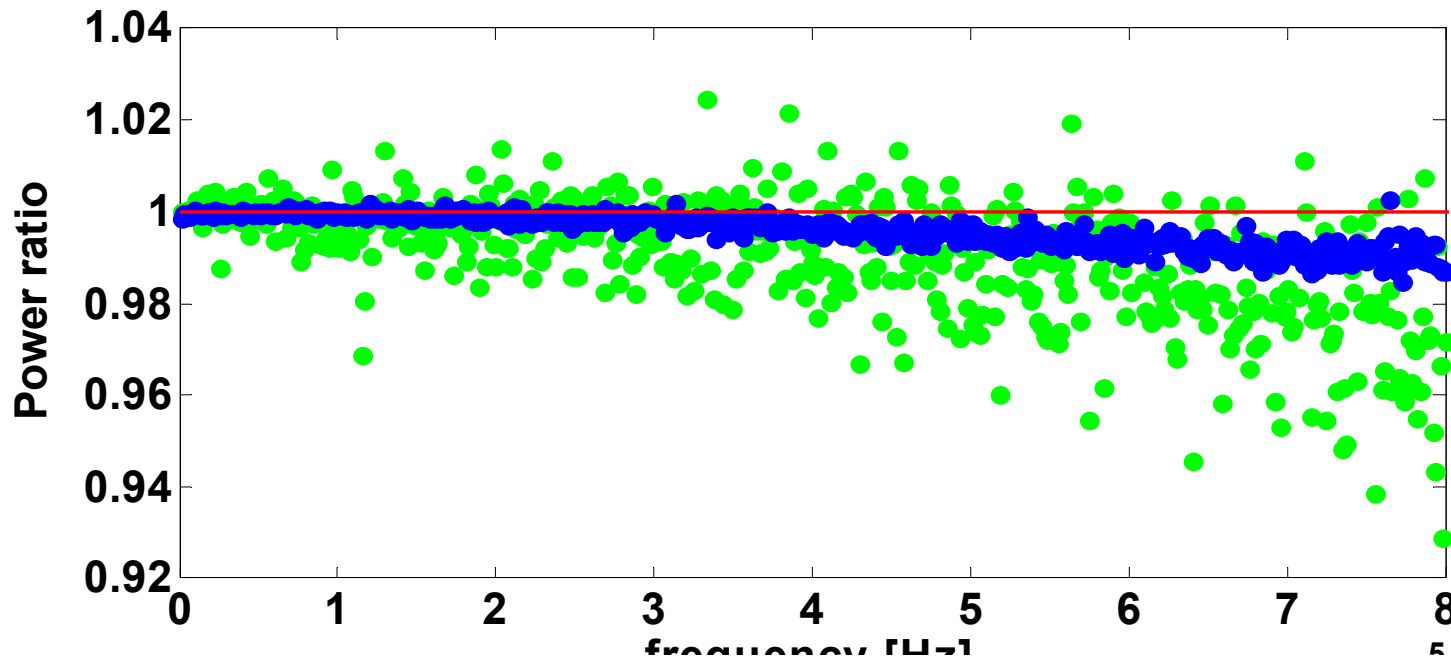
- Voltage noise of a resistor
  - Nyquist 1928
- Absolute temperature calibration
- Easy low voltage application of quantum voltage standard

$$\langle V_T^2 \rangle = 4kTR\Delta f$$

$$T = \frac{\langle V^2(T) \rangle}{\langle V_Q^2 \rangle} \frac{\langle V_{calc}^2 \rangle}{4kR}$$



# Impressive Accuracy At an Early Stage

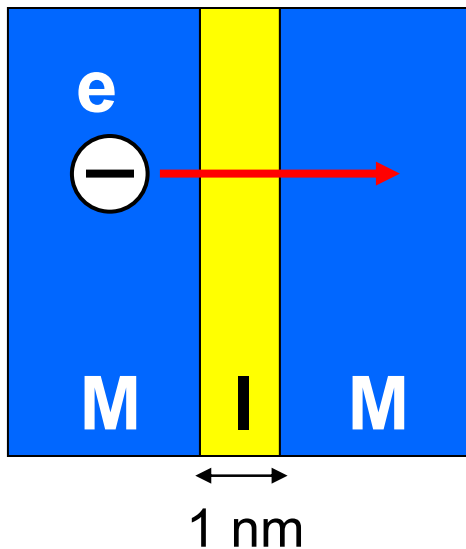


ITS-90 Definitions	Measured errors	
	5/2002	6/2003
$T_{ga} = 302.916 \text{ K}$	$-1330 \pm 1000 \text{ ppm}$	$+250 \pm 80 \text{ ppm}$
$T_{ga} / T_{wa} = 1.1092$	$+200 \pm 300 \text{ ppm}$	$+115 \pm 110 \text{ ppm}$

# Counting Electrons: Current and Capacitance Standard

What if you could count individual electrons?

Tunnel Junction



$$E_C \equiv \frac{e^2}{2C} \gg k_B T$$

Charging effect due to single electrons becomes important when  $E_C \gg k_B T$

$$E_C \sim 1 \text{ K for } (50 \text{ nm})^2 \text{ junction area}$$

# Electron Counting Capacitance Standard

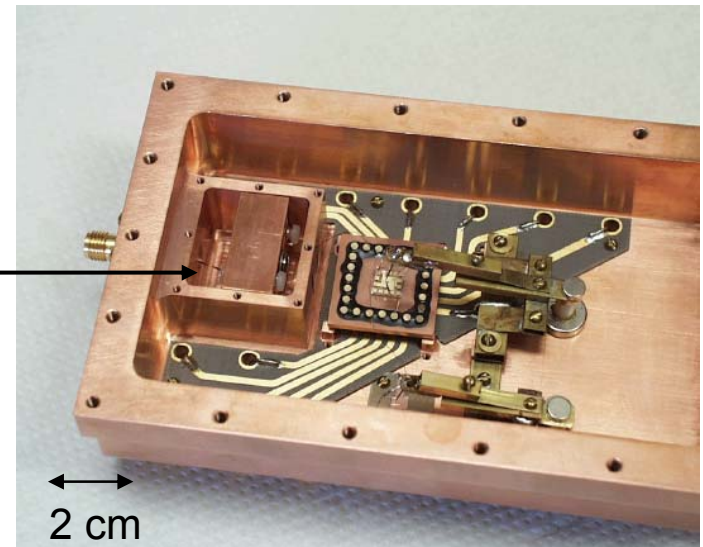
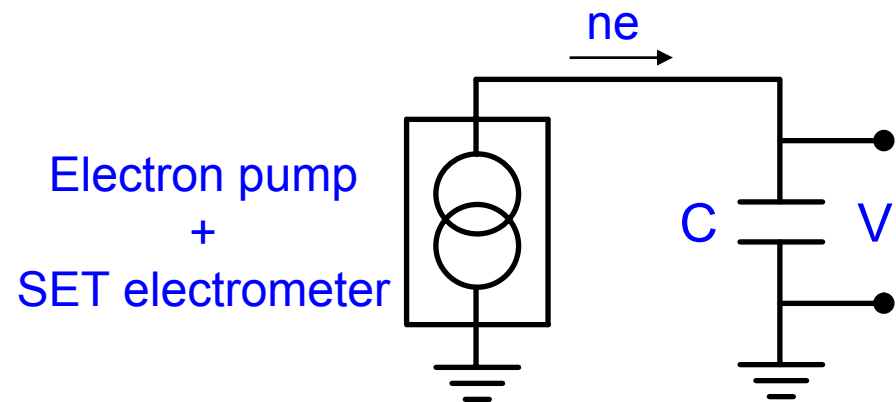
Directly implement definition of capacitance:  $C = Q/V = ne/V$

$$C \sim 1 \text{ pF}, V \sim 10 \text{ V} \\ \Rightarrow n \sim 10^8$$

- Provides a natural standard for capacitance based on quantized electron charge.

- Analogous to Josephson junction volt and quantum Hall ohm.

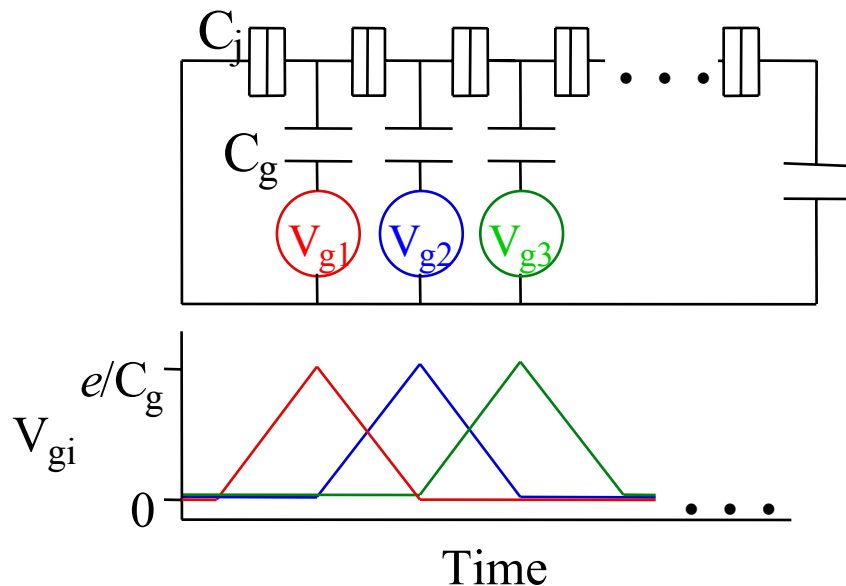
Vacuum gap capacitor: no dielectric  
 $\Rightarrow$  Ideal (frequency independent)  
(Electricity Division)



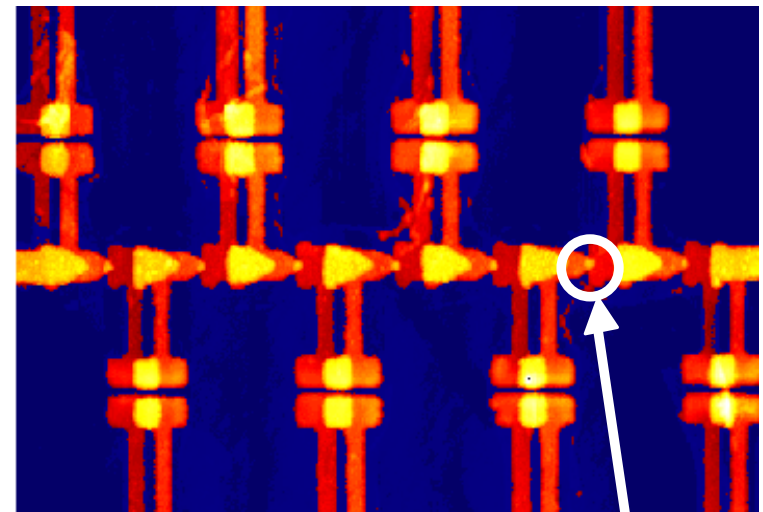
# Single Electron Pump

7-junction electron pump moves 1 electron through each time gates are pulsed in sequence.

Error rate: 1 electron in  $10^8$



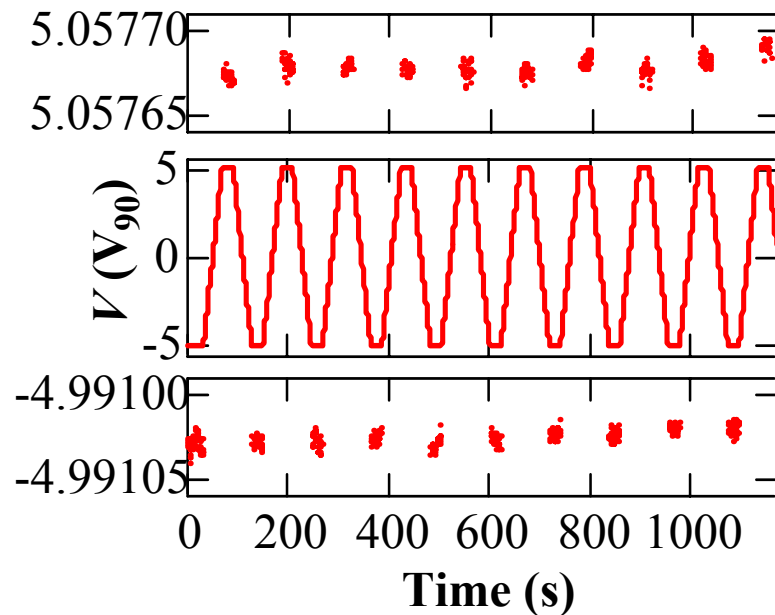
Pump frequency up to 5 MHz  
 $\Rightarrow$  1 pA current



1  $\mu\text{m}$

Tunnel  
junction  
-  $(40 \text{ nm})^2$

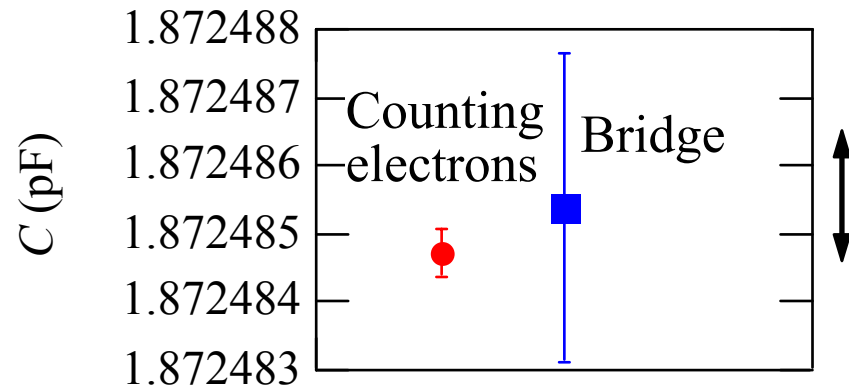
# Electron Counting Capacitance Standard



- Pump  $\sim 10^8$  ( $\pm 1$ ) e onto C
- Measure V (against JJ volt)

Calculate C

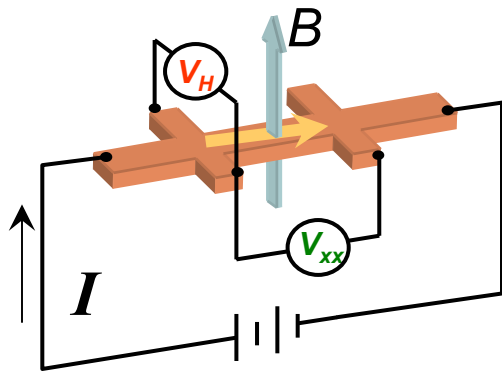
Reproducible to  $10^{-7}$



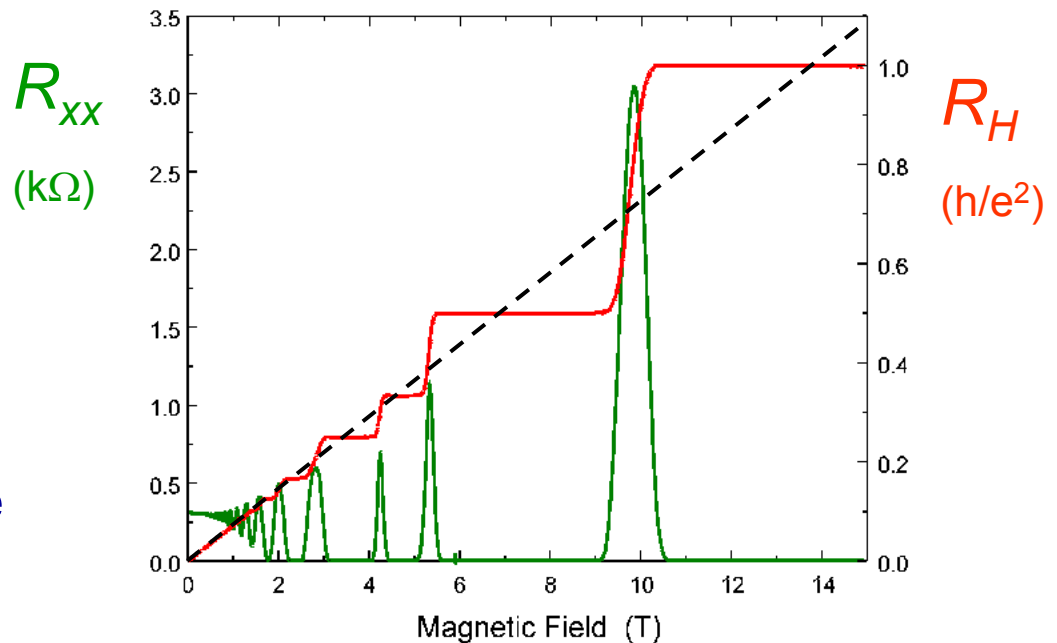
Compare ECCS value to SI farad  
(Transfer standard  $\pm 2 \times 10^{-6}$ )

Comparison at  $10^{-7}$  coming soon!  
Transportable unit under construction

# The Integer Quantum Hall Effect



GaAs semiconductor device

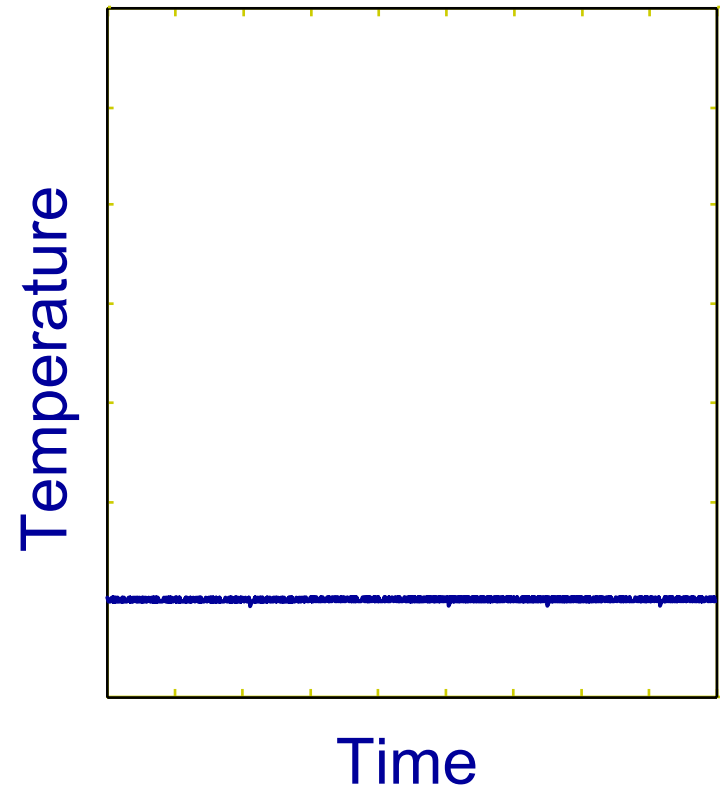
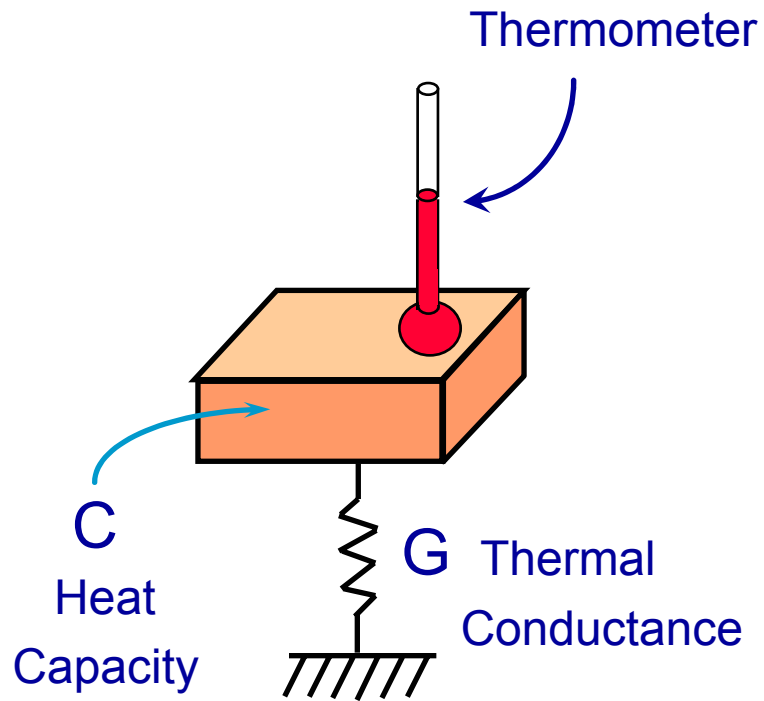


$$R_{Hall} = \frac{h/e^2}{j} = 25812.807 \text{ Ohms} / \text{integer}$$

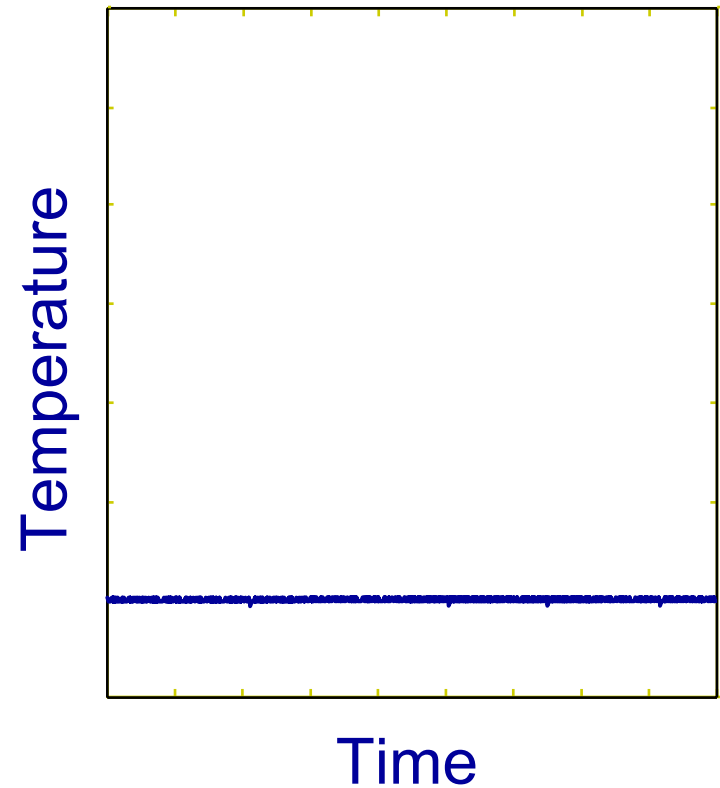
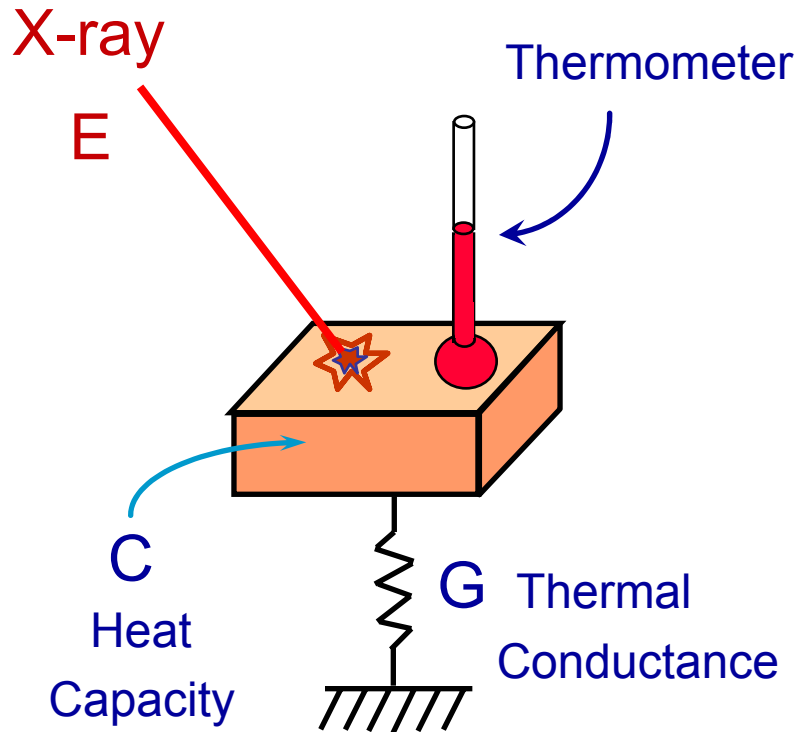
We use this quantum technology to realize resistance, but no fabrication facility yet at NIST

Courtesy of Prof. James Eisenstein, Caltech

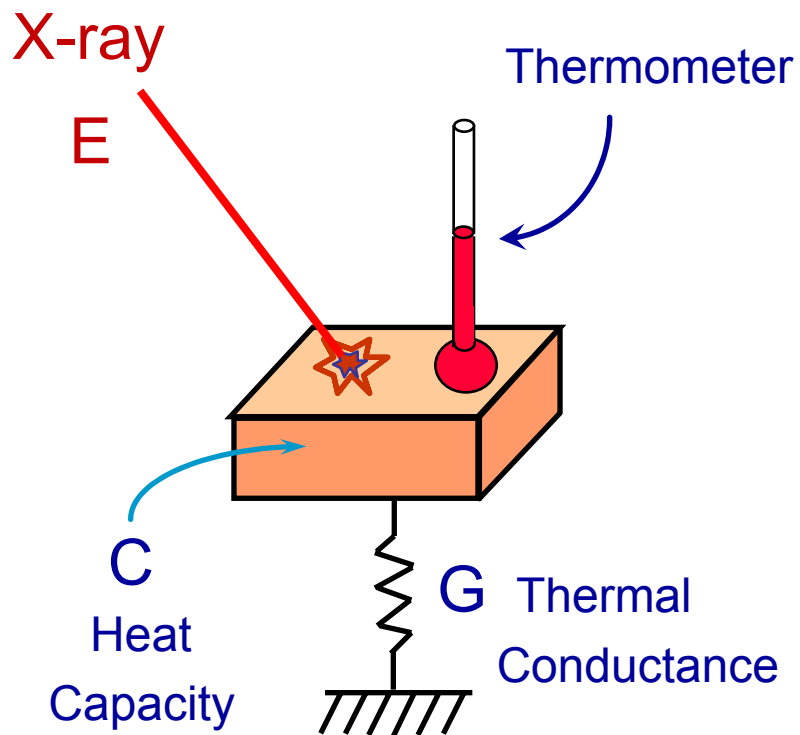
# Measurements Using Microcalorimeters



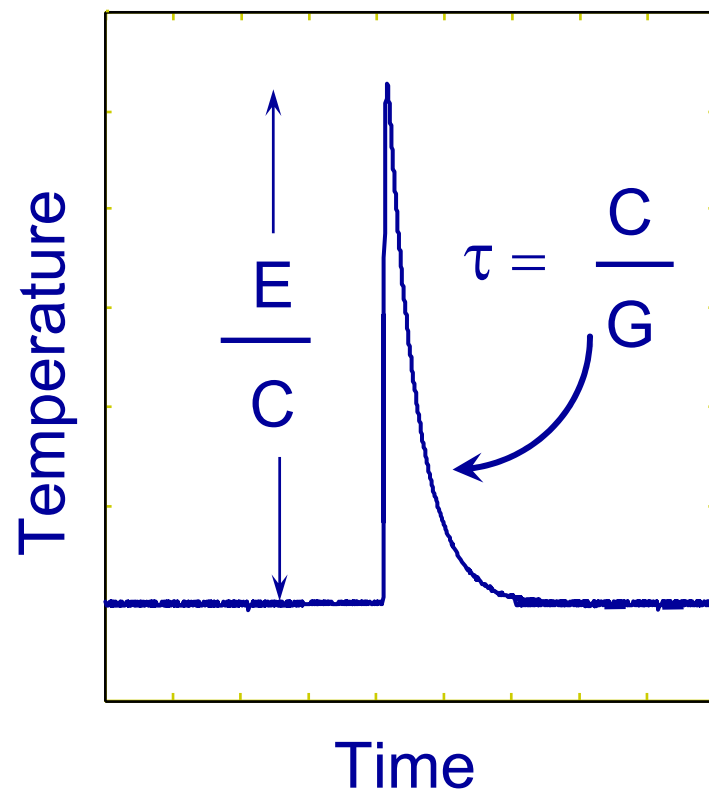
# Measurements Using Microcalorimeters



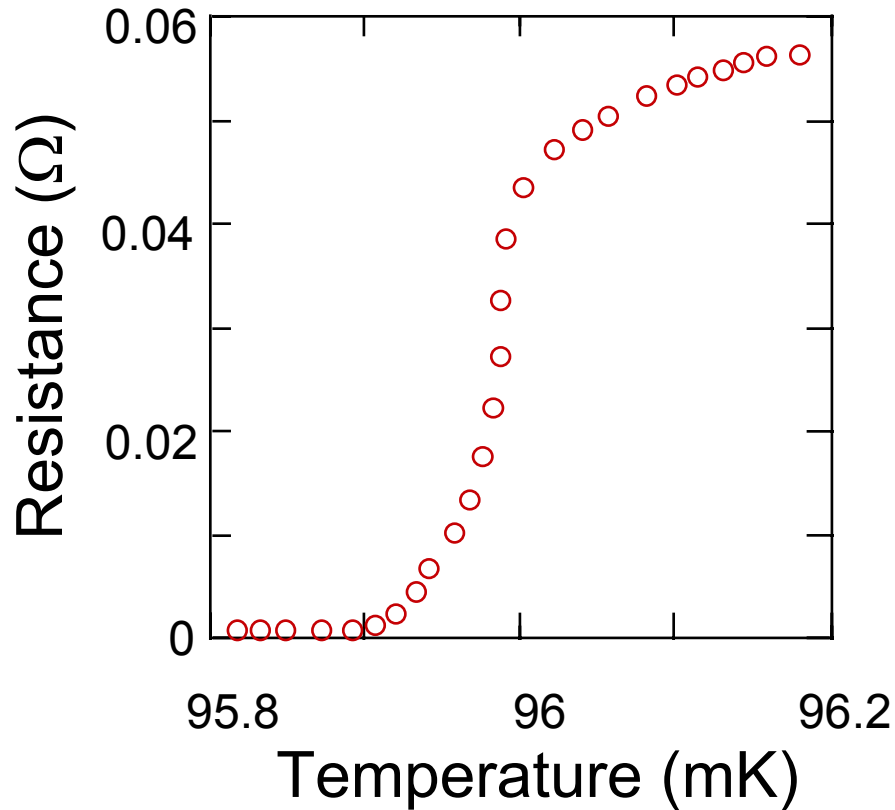
# Measurements Using Microcalorimeters



Photon  $\rightarrow$  Heat

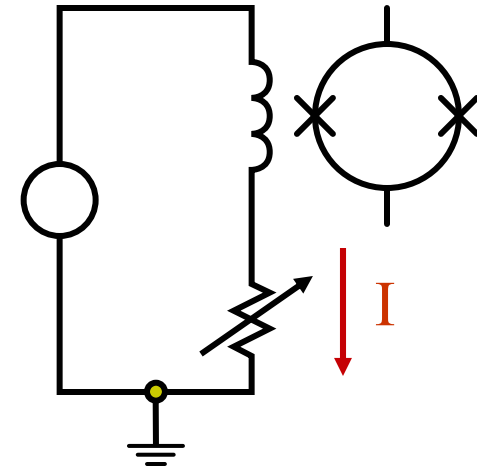
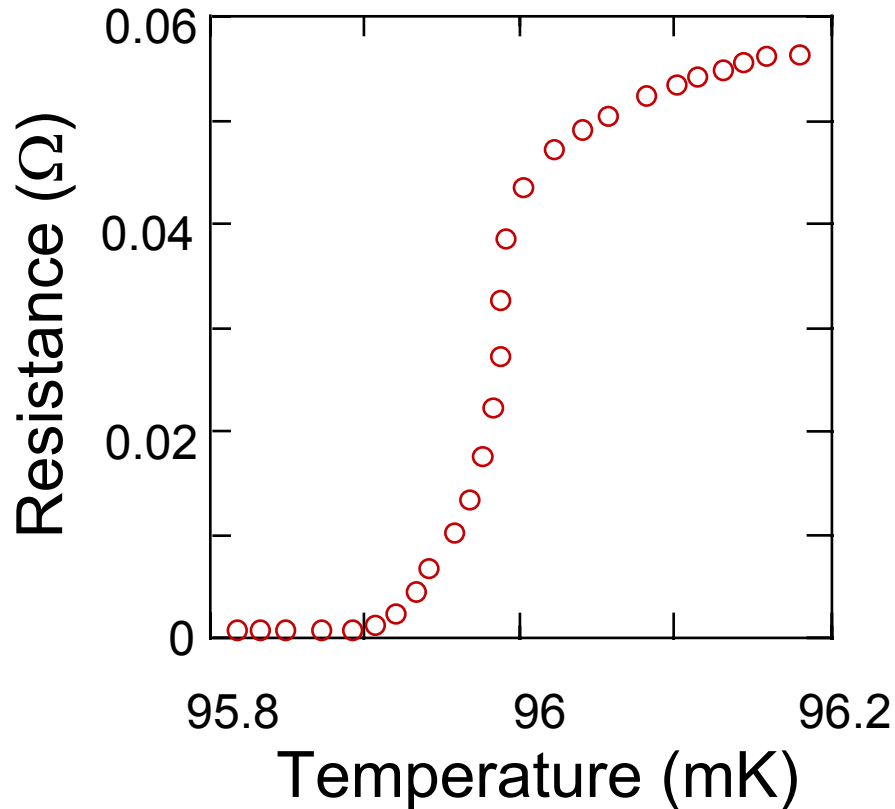


# Superconducting Transition-Edge Sensor



Photon  $\rightarrow$  Heat  $\rightarrow$  Resistance

# Superconducting Transition-Edge Sensor



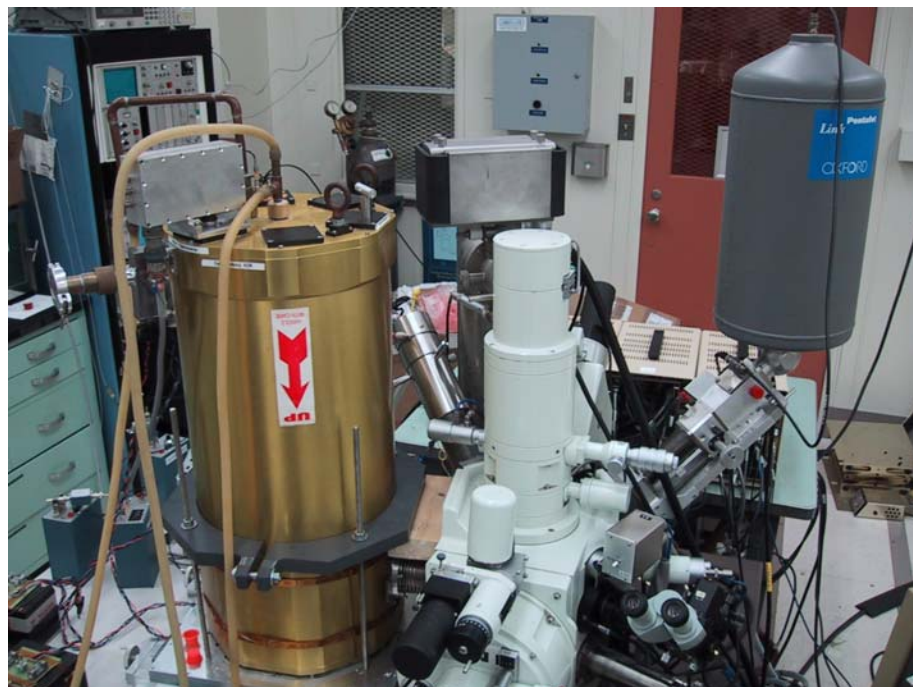
Photon  $\rightarrow$  Heat  $\rightarrow$  Resistance  $\rightarrow$  Current

# X-Ray Microanalysis Systems

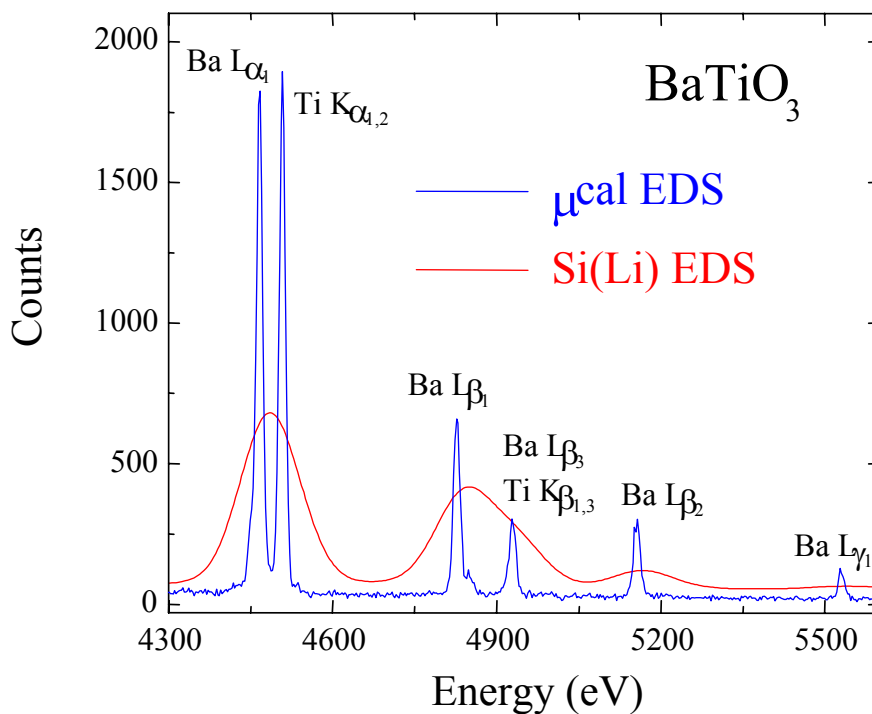
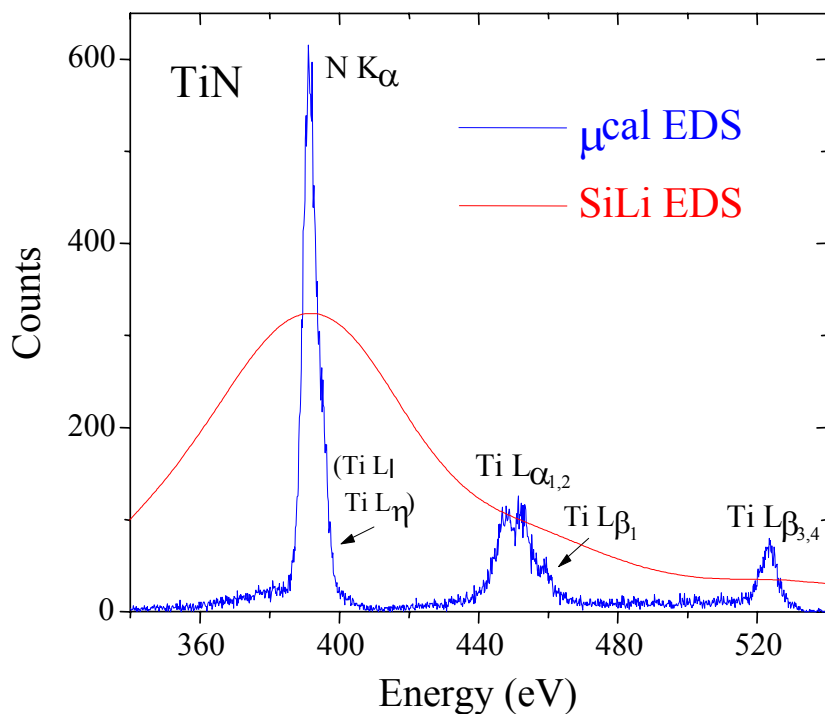
## NIST/Boulder EEEL



## NIST/Gaithersburg CSTL



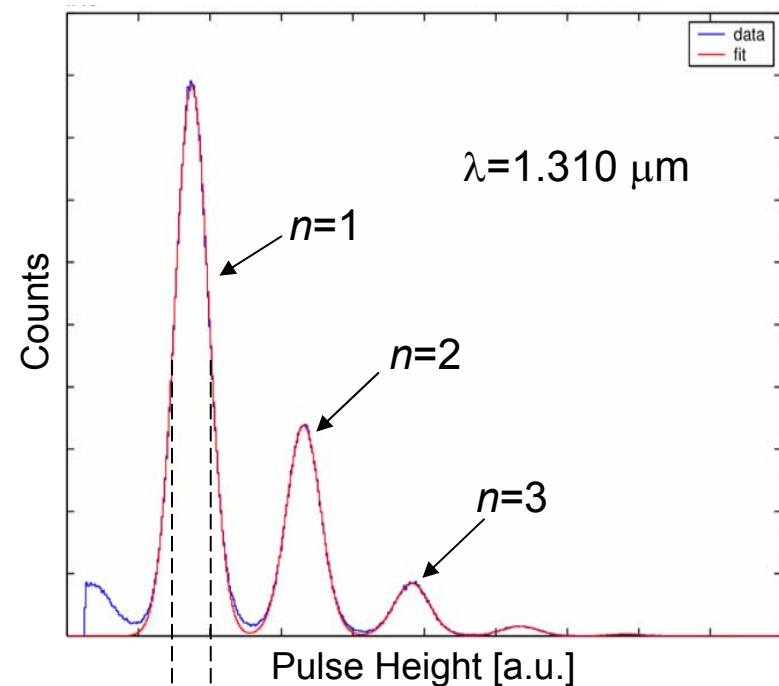
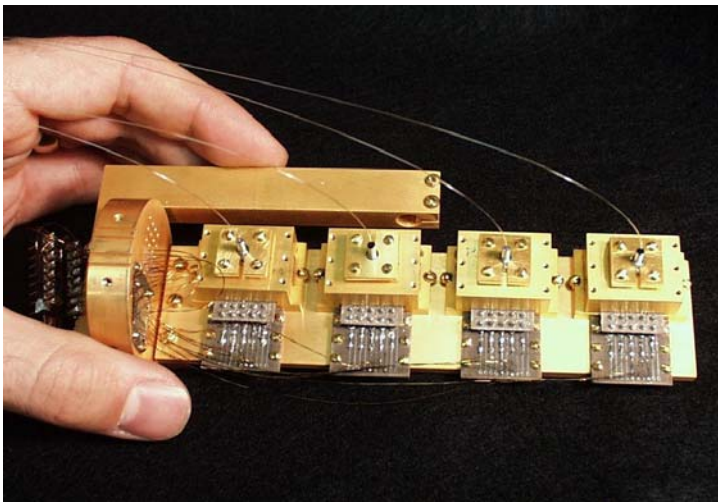
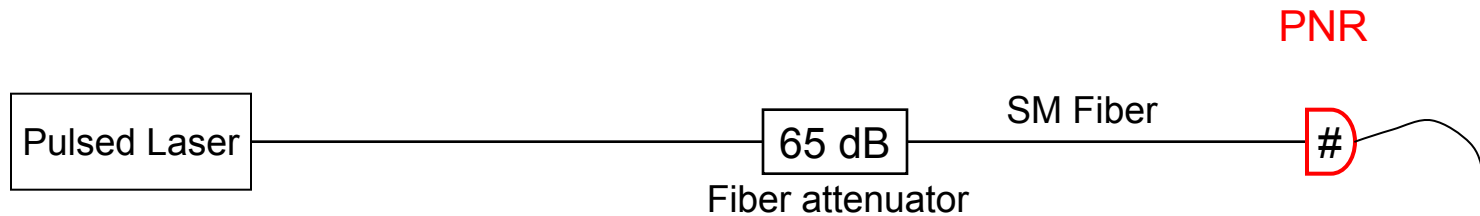
# High Energy Resolution for X-Ray Microanalysis



High resolution allows the resolution of x-ray line overlaps

Joint program with CSTL

# Counting Photons and Quantum Key Distribution



$\Delta E$  limited by thermal noise at 100 mK

Joint program with PL, ITL

# X-Ray Microcalorimeters in Use

- Demonstration systems for materials analysis at NIST Boulder and Gaithersburg
- One apparent commercial supplier of demonstration systems having similar technology
- Potential for defect analysis in semiconductor manufacturing
- Major effort in infrared through x-ray imaging
- Photon counting for quantum key distribution

# Summary of Quantum-Based Measurements and Standards

## For measurements and standards ...

- First generation voltage standard widely and critically used— about 100 locations
- Second generation used in about 10 locations
- Third generation used to demonstrate Johnson noise thermometry
- No apparent barriers to widespread use of SET capacitance standards
- Beginning commercialization of microcalorimeter x-ray detectors for use in materials analysis
- Can now count photons in a weak pulse of light for QKD

# What Can We Learn?

- Condensed matter quantum measurements and standards take advantage of the latest and most exciting science
- ... and they are practical!
- They offer remarkable capabilities— that cannot be accomplished any other way
- There is much important work left to do:
  - voltage, capacitance, current, imaging arrays, photon counting, quantum Hall

# What Can We Learn?

- Counting quanta is one step toward more precise measurements.
- With NIST's quantum computing (atomic, ionic, electronic charge, and condensed matter) efforts, we are learning not just how to count but also how to manipulate wave functions.
- In quantum-based measurements and standards, NIST is the best-in-the-world. With NIST's renewed commitment we must remain so.
- Stay tuned ...

# The People Who Did the Work

## Special thanks to

- ... dozens of collaborators at NIST
- ... and hundreds more around the world
- ... including standards labs in ...

Canada

China

Denmark

England

France

Germany

Japan

New Zealand

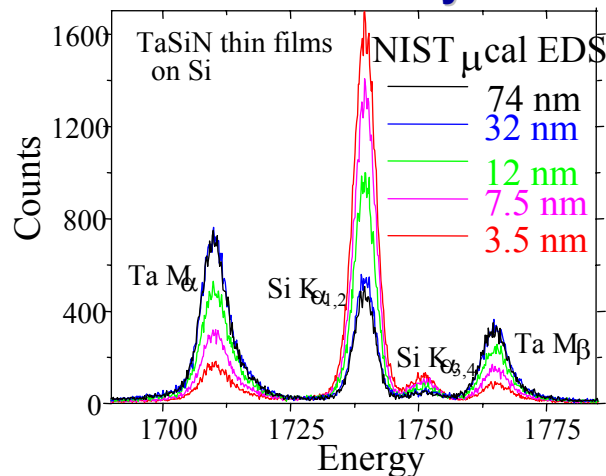
Switzerland

South Korea



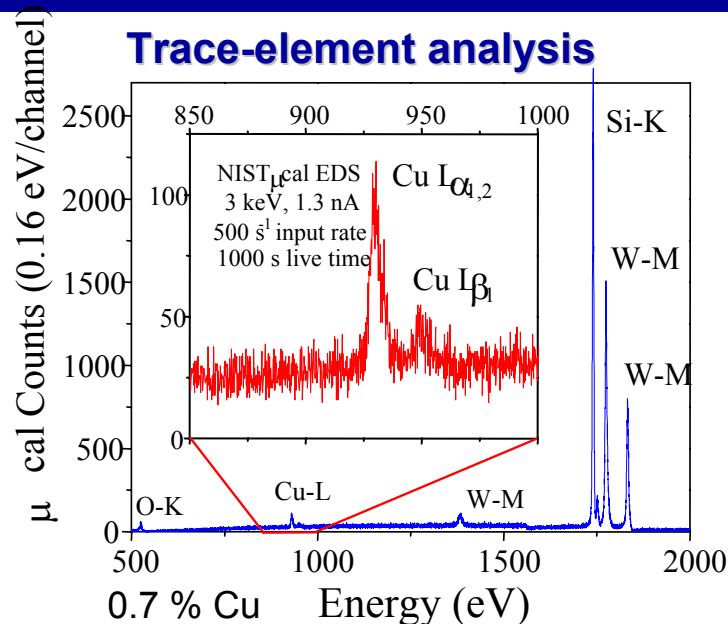
# High Energy Resolution for Microanalysis

## Thin-film analysis



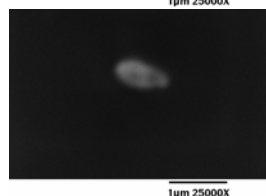
- High resolution provides high peak-to-background ratio, providing improved thin-film and trace-element analysis.
- Small shifts in x-ray line positions due to chemical bonding allows chemical-shift analysis

## Trace-element analysis



## Nanoscale particle analysis

### Al oxide particle



### Al particle

